SCIENCE

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THE STRUCTURE OF ATOMS, AND THE EVOLUTION OF THE ELEMENTS AS RELATED TO THE COMPOSITION OF THE NUCLEI OF ATOMS[1]

THE general theory of the structure of the atom which seems to be most closely in harmony with the facts is that developed by Rutherford. His theory assumes that the atom consists of a central nucleus or sun, and that the satellites of the miniature solar system are the negative electrons. The central nucleus is supposed to contain almost all of the mass of the atom, and is charged with positive electricity. That this nucleus is very minute in comparison with the size of the atom is indicated by the work of Rutherford, of Geiger and Marsden, and of Darwin, who find that the deflection of alpha particles, which are shot from radioactive atoms at speeds which approach 20,000 miles per second and so pass directly through other atoms, is of such a character as to indicate that the positive charge of the atom is very highly concentrated. Thus Darwin's work indicates that the maximum diameter of the nucleus of a hydrogen atom (1.7×10^{-13} cm.) is only about one-one hundred thousandth of the diameter usually assumed for the atom. On this basis the atom would have a volume a million-billion times larger than that of its nucleus, and thus the nucleus of the atom is much smaller in com-

[1] Address presented at the Symposium on the Structure of Matter at the New York meeting of the American Association for the Advancement of Science. A bibliography will be found in the following papers: *Jour. American Chemical Society,* 37, 1367–1421 (1915), 39, 856–879 (1917); *Philosophical Magazine,* 30, 723–734 (1915).

parison with the size of the atom than is the sun when compared with the dimensions of its planetary system.

The special modification of Rutherford's theory which has met with the most success is that due to Bohr. The very remarkable features of this theory have been made the subject of Professor Millikan's address, which has already been given, so they need not be mentioned here. However, in spite of its success, Bohr's theory possesses in common with the other special views of atomic structure which have been developed, the limitation that its application has been restricted to one special class of phenomena, those of radiation, and that it is too simple to give a mechanism which will act as any except the most simple of atoms. In the Bohr atom the negative electrons external to the nucleus are all supposed to lie in the same plane with the nucleus, while the structural relations of organic molecules seem to indicate that at least the outer electrons do not lie in a plane (except when only two in number) but that they have a three-dimensional arrangement.

It was found by Moseley that if the elements are arranged in order according to their X-ray spectra, they fall in the same order as they do in the periodic system. If arranged in this way, beginning with hydrogen as 1, and helium as 2, they are said to be arranged according to their atomic numbers. In our ordinary system of elements there are in all 91 elements from helium to uranium inclusive, and in addition to these there is hydrogen which makes 92 in all. Of these 86 or 87 have been discovered and 6 or 5 remain to be found. It is the purpose of this paper to present some relations which have been found by the writer and his students, which have a bearing on the structure of the atoms of these elements, upon the problem of their stability, and their formation by evolution.

1. Are the Elements Intra-atomic Compounds of Hydrogen?

One of the first suggestions in regard to the structure of the atom was made by Prout in 1815, or a little over a century ago. Prout found, on the basis of his own experiments and the more accurate work of Gay-Lussac, that if the atomic weight of hydrogen was put as 1.00, the atomic weights of the other elements became whole numbers as follows:

PROUT'S ATOMIC WEIGHTS (1815 A.D.) (WITH THE 1915 ATOMIC WEIGHTS ON HYDROGEN BASIS IN PARENTHESES)

Hydrogen	1.0	(1.000)
Carbon	6	(11.91)
Nitrogen	14	(13.90)
Phosphorus	14	(30.78)
Oxygen	16	(15.88)
Sulphur	16	(31.82)
Calcium	20	(39.76)
Sodium	24	(22.82)
Iron	28	(55.41)
Zinc	32	(64.86)
Chlorine	36	(35.46)
Potassium	40	(38.80)
Barium	70	(136.31)
Iodine	124	(125.94)

If Prout's atomic weights had proved exactly correct, his claim that hydrogen is the protyle (πρώτη ὑλη) or fundamental element, might have seemed justified, but when it was found that these weights were very far from correct his hypothesis was largely discarded.

The prejudice which existed a few years ago against Prout's idea is well shown by a quotation from von Meyer's "History of Chemistry," printed in 1906.

> During the period in which Davy and Gay-Lussac were carrying on their brilliant work, and before the star of Berzelius had attained to its full luster, a literary chemical event occurred which made a profound impression upon nearly all the chemists of that day, viz., the advancement of Prout's hypothesis. This was one of the factors which materially depreciated the atomic doctrine in the eyes of many eminent investigators. On ac-

count of its influence upon the further development of the atomic theory this hypothesis must be discussed here, although it but seldom happens that an idea from which important theoretical conceptions sprang, originated in so faulty a manner as it did.

However, a careful study of the most accurately determined of the recent atomic weights reveals some very remarkable relationships. If first of all we make the assumption, as a subject for argument, that the heavier atoms are built up from hydrogen atoms, then it is found that the atoms are in nearly all cases lighter than they should be on the basis of such an hypothesis. Thus, if the following atoms of low atomic weight are considered, it is found that nearly all of them weigh 0.77 per cent. too little.

TABLE I

Atom of	Atomic Weight	Difference from a Whole Number	Per Cent. Variation
Helium.......	3.97	−0.03	−0.77
Boron........	10.92	−0.08	−0.77
Carbon.......	11.91	−0.09	−0.77
Nitrogen......	13.90	−0.10	−0.70
Oxygen.......	15.88	−0.12	−0.77
Fluorine......	18.85	−0.15	−0.77
Sodium.......	22.82	−0.18	−0.77

Therefore, if these atoms are built from hydrogen atoms, there must be during their formation a loss in weight, and presumably in mass, equal to 0.77 per cent. This will be called the "packing effect." When all of the 26 elements from helium of atomic number 2, to cobalt (No. 27) are considered, it is found that with the exception of the four elements, beryllium, magnesium, silicon, and chlorine, which have atomic weights higher than the corresponding nearest whole numbers, the average packing effect of the elements is again −0.77 per cent. This constancy of the packing effect suggests that the variation is due to some single cause, though the four exceptional cases cited above, show that there is undoubtedly some other complicating factor. The discovery by Thomson and Aston that the similar exceptional case of neon is due to the admixture of an isotope of higher atomic weight suggests that it may not be impossible to find a cause for the exceptional behavior in the four other cases.

It has formerly seemed difficult to explain why the atomic weights referred to oxygen (16.00) as a basis are so much closer to whole numbers than those referred to hydrogen as 1.00, but the explanation is indeed very simple from the point of view presented here. The closeness of the atomic weights on the oxygen basis to whole numbers, is indeed extremely remarkable. Thus for the eight elements from helium to sodium the average deviation is only 0.02 unit, or less than the average probable error of the atomic weight determinations, and for all of the first 27 elements the average deviation from a whole number is, though more, increased only to 0.09 unit, when the *sign* of the deviation is considered. If it is *not* considered the deviation is reduced to 0.01 unit for 21 elements. The probability that such values as these could be obtained by accident is altogether unworthy of consideration. If an oxygen atom is a structure built up of 16 hydrogen atoms, then according to the ordinary theory that mass and weight are strictly additive, the weight of an atom of oxygen should be exactly 16 times the weight of a hydrogen atom. Now, according to the present system of atomic weights the weight of an atom of hydrogen is taken as 1.0078, so the oxygen atom should weigh 16.125. However, it is found to weigh 16.00. The difference between 16.125 and 16.000 is the value of the packing effect, and *if this effect were exactly the same for all of the elements except hydrogen, then the choice of a whole number as the atomic weight of any one of them, would, of necessity, cause all of the other atomic weights*

to be whole numbers. Though this is not quite true, it is seen that the packing effect for oxygen is 0.77 per cent., which is the average packing effect for the twenty-one elements considered (elements of low atomic number). Therefore these elements, which have packing effects equal to that of oxygen, will have whole numbers for their atomic weights. Since, too, the packing effect is very nearly constant, all of these 21 elements will have atomic weights close to whole numbers.

While according to our ordinary experience mass and weight seem to be additive, the question may be raised whether in the formation of atoms, which is a process which is, up to the present time, outside our experience, this is true. There are three remarkable facts to be explained: first, the atomic weights of the lighter elements on the *hydrogen* basis approximate whole numbers; second, the deviations from whole numbers are *negative,* and third, these deviations are practically constant in magnitude.

It has been already stated that according to the work and calculations of Darwin, and of Geiger and Marsden, the nucleus of the atom is extremely minute in comparison with the size of the atom, so that in the nucleus the mass, if the determined dimensions of atoms and their nuclei are at all correct, is many thousand billion times more concentrated than in the atom. If the nucleus is complex, the electromagnetic fields of the charged particles would be extremely closely intermingled in the nucleus, and it would seem reasonable to assume that this would affect the mass, so that the mass of the whole nucleus would not be equal to the sum of the masses of its parts.

Let us take an extremely simple case for calculation, and find how closely packed the charged particles in a nucleus would have to be to cause the observed decrease in weight (0.77 per cent.) which is found for most of the atoms. In making such a calculation, as a guide for our assumptions, we have the observed fact that radioactive atoms shoot out both positively charged alpha particles and negative electrons at such high speeds that it seems probable that they come from the *nucleus of the atom.* The observed relations between the products of the radioactive changes support this idea very strongly indeed. Thus there seem to emerge from the nuclei of complex atoms both positively and negatively charged particles, and the negatively charged particles are found to be negative electrons. This point should be emphasized, since many workers on atomic theory have endeavored to construct their imaginary nucleus of positively charged particles alone.

The simplest case for calculation[2] would then be for a nucleus consisting of one positive and one negative particle. Let the distance between the particles be d, the charges respectively e_1 and e_2, let the velocity of the particles be along the straight line connecting them and equal to u. Then if c is the velocity of light, the particles have a longitudinal momentum which differs from the momentum calculated by ordinary mechanics for electrically neutral particles possessing mass by an amount equal to

$$2\frac{u}{c^2}\cdot\frac{e_1e_2}{d}.$$

This may be called the mutual electromagnetic momentum of such a system of particles. The mutual electromagnetic mass corresponding to this is

$$\Delta m_1 = \frac{2}{c^2}\cdot\frac{e_1e_2}{d} = \frac{2}{c^2}\frac{e^2}{d} \quad \text{since } e_1 = e_2.$$

[2] For this calculation see the following papers by Harkins and Wilson: *Proc. Nat. Acad. Sciences,* 1, 277–78 (1915); *J. Am. Chem. Soc.,* 37, 1373–78 (1915), and *Phil. Mag.,* 30, 725–28 (1915).

The corresponding mass of one particle is

$$m_1 = \frac{2}{3}\frac{e^2}{c^2 R},$$

where R is the radius of the electron; so

$$\frac{\Delta m}{m_1} = \frac{3R}{d}.$$

In the application of this last equation, R is to be taken as the radius of the positive electron, since it is assumed that it is the seat of practically all of the mass of the atom. In order to produce a decrease of mass equal to 0.77 per cent., which is the average decrease in weight as calculated from the atomic weights, the two electrons should approach until their distance is 400 times the radius of the positive electron. Thus a packing effect of 0.77 per cent. would be produced by a moderately close packing of the electrons in the nucleus.

The packing effect for oxygen, which has been taken as the basis for our modern atomic weights, is exactly equal to the average value given above. If the number representing the atomic weight of hydrogen on the oxygen basis, 1.0078 is decreased by this percentage amount, it becomes equal to 1.000, so the oxygen system of atomic weights may be considered as a hydrogen system, with hydrogen taken as 1.000, but where the weight of the hydrogen atom is taken *after* it has been subjected to the average packing effect of 0.77 per cent. Thus in going over from the hydrogen to the oxygen system of atomic weights, the chemists who made the change were, without knowing it, making allowance for the average packing effect, for, while the atomic weight of hydrogen is 1.0078, the atoms heavier than hydrogen have atomic weights which are near what they should be if they were built up of units of weight very close to 1.000. On the other hand, this unit of mass must be somewhat variable to give the atomic weights as they are, even although a part of the variation, in some cases, may be due to the inaccuracy with which the atomic weights are known. This leads either to the supposition (1) that the atoms are built up of some unknown elementary substance, of an atomic weight which is slightly variable, but is on the average extremely close to 1.000, and which does not in any case deviate very far from this value, or to the idea (2) which is presented in this paper, that the *nucleus* of a known element is the unit of structure. The atom of this known element has a mass which is close to that of the required unit, and it has been proved that the decrease of mass involved in the formation of a complex atom from hydrogen units is in accord with the electromagnetic theory. The adoption of the first hypothesis would involve much more complicated relations. It would necessitate the existence of another elementary substance with an atomic weight close to that of hydrogen, it would involve a cause for the increase of weight in the formation of some atoms, and a decrease in other cases, and it would also involve the existence of another unit to give the hydrogen atom.

It may be well to consider here the *probability* that the elements from helium to cobalt, atomic numbers 2 to 27, may have atomic weights as close to whole numbers as they are on the oxygen basis, entirely by accident. For example we may calculate the chance that each of the atomic weights should be as close as it is to a whole number, and we find that there is one chance in five thousand billion billion. Another probability is that the sum of the deviations from whole numbers shall not exceed the sum found experimentally. This gives the result that there is one chance in fifteen million. Thus, in the words of Laplace as applied to a calculation of probability in connection with an astronomical problem, that the atoms are built up of units very close to one, "est indiquée avec un pro-

babilité bien supérieure à celle du plus grand nombre des faits historiques sur lesquels on ne se permet aucune doute.''

THE ATOMS ARE INTRA-ATOMIC HELIUM-HYDROGEN COMPOUNDS

The atoms of radioactive substances are known to shoot off alpha particles with speeds as high as 20,000 miles per second. These alpha particles carry two positive charges, have an atomic weight of 4.0, and when they are collected and take up negative electrons, give ordinary helium. They may be thought of as the nuclei of helium atoms, and seem to be shot out from the *nucleus* of the more complex atom such as that of radium or thorium. Fig. 1 illustrates the change which occurs in this process. Any special element, such as radium (which is an extremely active solid, with a valence of 2, and belonging therefore to group 2) has its valence reduced by two when the atom ejects an alpha particle (which carries two positive charges), and in this case changes into the inactive gas, radium emanation or niton. The alpha particle has a weight of 4, and niton has an atomic weight which is 222, or four less than that of radium (226). That this is a general rule was discovered by Soddy, and it was verified later by Fajans, Russell, von Hevesy and Fleck.

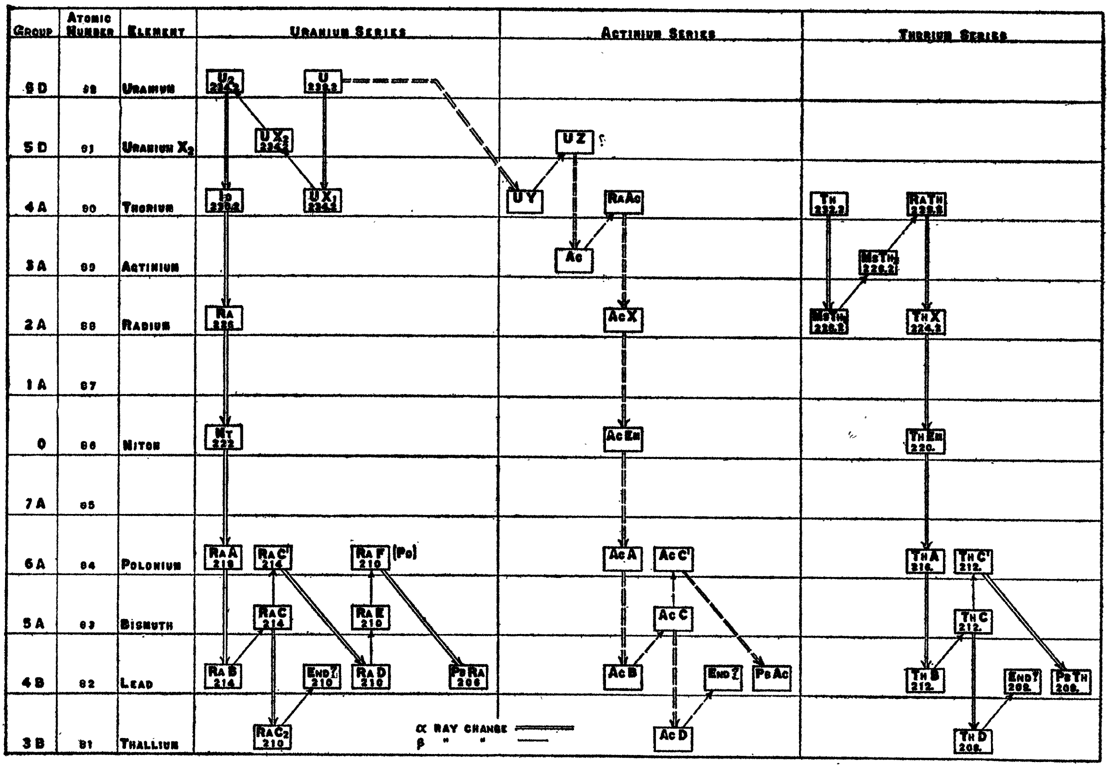

FIG 1. TRANSFORMATIONS OF THE RADIOACTIVE ELEMENTS. The α and β changes of the radio-active elements. Note that the atoms of even atomic number are more numerous than those of odd atomic number. Thus there are 32 of the former class to 11 of the latter.

Let us picture the changes which occur during the long chain of processes which

converts Uranium 2 into Radium B, which is a variety (isotope) of the element lead. We will assume that the nucleus of a uranium 2 atom, so far as its composition, but not its constitution, is concerned, is made up of the nucleus of a Radium B atom (which nucleus we will designate by $(RaB)_n$, where the subscript n denotes that it is the nucleus only), and 5 α^{++} particles, where the two plus signs serve to remind us that the alpha particle carries a double positive charge. Then the changes which occur, beginning with Uranium 2, and ending with Radium B, are such that in each successive change one of these α^{++} particles is emitted by the nucleus.

According to this table it would seem that when the nucleus of an atom loses an α^{++} particle, and thus decreases its positive charge by two, the outer atom must lose two negative electrons in order to keep the atom electrically neutral. That this is actually the case seems to be indicated by the fact that there is evidence in the chemical properties that the number of valence electrons decreases by two. According to this idea, when the nucleus shoots out an α^{++} particle, the atom, as a whole, loses an entire helium atom by the time it becomes electrically neutral. That the loss of the negative electrons in alpha disintegrations has not been detected is probably due to the low velocities with which such external electrons leave the outer part of the atom.

TABLE[3]

The Changes in the Composition of the Nuclei of Atoms when they eject Alpha Particles (Nuclei of Helium Atoms) of Weight 4, and carrying Two Positive Charges, with Corresponding Changes in the Non-nuclear Electrons

Group	Atomic Number	Name of Element	Atomic Weight	Composition of Nucleus	+ Charge on Nucleus	Number of Inner Non-Nuclear —Electrons	Number of Valence Electrons
6	92	Uranium 2	234	$82 + (RaB)_n + 5\alpha^{++}$	(Note 3) $82 + 10 = 92$	86	6
4	90	Ionium	230	$82 + (RaB)_n + 4\alpha^{++}$	$82 + 8 = 90$	86	4
2	88	Radium	226	$82 + (RaB)_n + 3\alpha^{++}$	$82 + 6 = 88$	86	2
0	86	Niton	222	$82 + (RaB)_n + 2\alpha^{++}$	$82 + 4 = 86$	86 (Decrease here by 8)	0
6	84	Radium A (Isotope of Polonium)	218	$82 + (RaB)_n + 1\alpha^{++}$	$82 + 2 = 84$	78	6
4	82	Radium B	214	$82 + (RaB)_n$	$82 + 0 = 82$	78	4

[3] The most doubtful feature of this table is the assumption that the nuclear charge is equal to the atomic number, but the insertion of $92 + \mu$ for 92, of $90 + \mu$ for 90, etc., where μ is a whole number, and probably either zero or else very small, removes this doubtful feature.

THE ELEMENTS OF EVEN ATOMIC NUMBER, OR HELIUM SERIES ELEMENTS

While the alpha disintegrations of atoms are known only among the heaviest atoms, and extend downward from element ninety-two (uranium) to element eighty-two (lead), it occurred to me several years ago that this system undoubtedly should extend downward still further, and quite possibly even to the lightest elements. The indication that the system still holds should be found in the atomic weights, for these should increase in steps of four between the atoms of even number. Thus the atomic weights of the lighter elements, if *exactly* this same system holds, should be as follows:

Atomic Number	Atomic Weight
2	4
4	8
6	12
8	16
10	20
12	24
14	28
16	32

Now, the extremely remarkable fact is that *the atomic weights given above are the atomic weights of the even numbered elements,* with only one exception.

If the twenty-six elements from helium to cobalt (atomic weights from 4 for helium to 59 for cobalt), inclusive, are considered, it might be assumed that the even numbered, or one half of the elements, should have atomic weights divisible by 4. Indeed, while there are two exceptions to the exact system, just 13 of these elements do have such atomic weights, and every possible multiple of 4 but one is taken, as is shown in the following table:

$1 \times 4 =$ helium
$2 \times 4 =$ missing, and replaced by $2 \times 4 + 1$
$3 \times 4 =$ carbon
$4 \times 4 =$ oxygen
$5 \times 4 =$ neon
$6 \times 4 =$ magnesium
$8 \times 4 =$ sulphur
$9 \times 4 =$ missing, but replaced by $10 \times 4 =$ argon
$10 \times 4 =$ calcium
$11 \times 4 =$ scandium
$12 \times 4 =$ titanium
$13 \times 4 =$ chromium
$14 \times 4 =$ iron

Thus, since the *even-numbered* elements of *high atomic weight* give off *helium atoms* when they disintegrate, and in such a way that for each helium atom lost the *heavy atom* changes into the atom of the element which has an *atomic number which is smaller by 2;* and since the *even numbered elements* of *low atomic weight* have *atomic weights which increase by four, or the atomic weight of helium, for each increase of 2 in the atomic number, the natural assumption is that the even numbered elements are compounds of helium.* To distinguish them from chemical compounds they may be called intra-atomic. At least for the elements of low atomic number, their general formula is *nHe′*, where the prime is added to indicate an intra-atomic compound.

THE ELEMENTS OF ODD ATOMIC NUMBER, OR ELEMENTS OF THE HELIUM-H_3 SERIES

If the odd-numbered elements, beginning with atomic number 3, or lithium (atomic weight $= 7$), are built up according to a

TABLE III

The Helium—H_3 System of Atomic Structure $H = 1.0078$

	0	1	2	3	4	5	6	7	8	
At. No.	2	3	4	5	6	7	8	9		
	He	Li	Be	B	C	N	O	F		
Ser. 2..	He	$He+H_3$	$2He+H$	$2He+H_3$	3He	$3He+H_3$	4He	$4He+H_3$		
Theor..	4.00	7.00	9.0	11.0	12.00	14.00	16.00	19.00		
Det...	4.00	6.94	9.1	11.0	12.00	14.01	16.00	19.00		
At. No.	10	11	12	13	14	15	16	17		
	Ne	Na	Mg	Al	Si	P	S	Cl		
Ser. 3..	5He	$5He+H_3$	6He	$6He+H_3$	7He	$7He+H_3$	8He	$8He+H_3$		
Theor..	20.0	23.0	24.00	27.0	28.0	31.00	32.00	35.00		
Det...	20.0	23.0	24.32	27.1	28.3	31.02	32.07	35.46		
At. No.	18	19	20	21	22	23	24	25	26	27
	A	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co
Ser. 4..	10He	$9He+H_3$	10He	11He	12He	$12He+H_3$	13He	$13He+H_3$	14He	$14He+H_3$
Theor..	40.0	39.00	40.00	44.0	48.0	51.0	52.0	55.00	56.00	59.00
Det...	39.9	39.10	40.07	44.1	48.1	51.0	52.0	54.93	55.84	58.97

Increment from Series 2 to Series $3 = 4He$. Increment from Series 3 to Series $4 = 5$ He (4 He for K and Ca). Increment from Series 4 to Series $5 = 6He$.

similar system, their atomic weights should be as follows:

Atomic Number	Atomic Weight
3	7
5	11
7	15
9	19
11	23
13	27
15	31
17	35
19	39

There is here again the remarkable fact that with one exception these are the atomic weights of the odd-numbered elements. The general formula for the odd-numbered elements may be expressed as $\mathrm{nHe}' + \mathrm{H}_3'$. From the numerical standpoint it will be seen that the system here proposed corresponds to the formulas found for the atomic weights by Rydberg in 1897. He found that most of the atomic weights can be expressed by $2m$ or $2m - 1$, where m is a whole number.

The proposed structure for the 26 elements of low atomic number is presented in Table III. While it is not meant that in every minute detail this table is necessarily correct, very strong evidence has been found for its validity as a general relationship.

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(*To be continued*)

SCIENTIFIC EVENTS

CHEMICALS AND WAR IN ENGLAND

PROFESSOR W. J. POPE, addressing a meeting of teachers at the Regent-street Polytechnic on October 6, according to a report in the London *Times*, said that Germany prepared for war by the establishment of a huge chemical industry, which was built up about the coal-tar industry, and then by exporting a very large proportion of the world's requirements of coal-tar colors, and pharmaceutical and photographic products.

That success was achieved in spite of the fact that England once possessed the whole of the heavy chemical industry of the world. We formerly produced practically all the nitric and sulphuric acids, and the greater part of the alkali used throughout the world. That had been taken from us as the result of Germany's foresight and exploitation of scientific ability. The coal-tar industry was established originally in this country. Until ten years ago Germany was practically dependent on us for crude coal-tar, and for the simpler first products separated from coal-tar.

Alluding to the establishment of the department for scientific and industrial research with an endowment of £1,000,000, Professor Pope said: The question we want answered is why that experiment was not made twenty years ago, at a time when it would have been undoubtedly successful in preventing the horrors of the last three years? We have suffered in the past from the exclusively British method of making the specialist entirely subservient to the administrator, the administrator being generally chosen because he is available, because he is politically acceptable, and because he knows nothing whatever about the subject which is to be administered and is therefore not likely to be prejudiced by any previous convictions. That process of appointing someone who knows nothing, to supervise the work of some one who does know how to do the job, seems to have been at the bottom of a great many of our misfortunes in the past.

Even in 1915 the government applied this same method to reestablish the coal-tar industry in this country. An organization was established in which all the people in control were men who knew nothing whatever about chemistry or science, and naturally enough the government organization has proved not only a great failure, but has had the further effect of inhibiting the reestablishment of the coal-tar industry. That is to say, the organization apparently was to do everything that was necessary, and consequently private effort was to a considerable extent hampered, and could not get on with the important problem of reestablishing this fine chemical industry.